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This AFOSR-supported research was aimed at realizing several chip-scale optical devices needed as building blocks for implementing integrated optical systems. To achieve this, we developed several theoretical, fabrication, and characterization tools and procedures for photonic crystals. Some of the main achievements of the previous AFOSR-funded research at the device level are as follows:

- (1) Photonic crystal waveguides (PCWs) with low loss, large transmission bandwidth, and very low dispersion and distortion in their pass-band for efficient guiding of light; the bi-periodic PCW proposed and demonstrated in our research has shown the best performance among all proposed PCW structures in terms of low propagation loss and available guiding bandwidth;
- (2) Photonic crystal superprism-based demultiplexers for compact separation of spectral channels in an integrated platform; the focusing superprism idea proposed and experimentally demonstrated for the first time within this program carries the world record on PC demultiplexing in integrated platforms with at least two orders of magnitude smaller size (while having the same performance) compared to all existing implementations of the same structure;
- (3) Theoretical prediction of very compact photonic crystal couplers with performance that cannot be achieved in other integrated platforms;
- (4) Theoretical investigation and demonstration of optical cavities with high quality factors.

The fabrication techniques to reliably make these structures have also been optimized. The fabrication quality of the photonic crystal structures fabricated in our group recently is at the best level achieved in academia with similar fabrication equipment. The high fabrication quality of the structures is in part due to the available state-of-the-art JEOL electron beam lithography system at the microelectronic research center (MiRC) at Georgia Tech, the state-of-the-art inductively coupled plasma (ICP) etching machine owned by Adibi's group (acquired through an AFOSR DURIP grant), and our extensive efforts in the optimization of the fabrication process for the high-quality photonic crystal structures.

Final Report to the
Air Force Office of Scientific Research (AFOSR)

Chip-Scale WDM Devices using Photonic Crystals

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I. Introduction

This report summarizes achievements in Dr. Adibi's research group at Georgia Institute of Technology in the area of chip-scale WDM devices using photonic crystals supported by Air Force Office of Scientific research (AFOSR) during the 3 year term of the program that started in May 2003. This AFOSR-supported research has been directed toward realizing low-loss large-bandwidth guiding and demultiplexing requirements of WDM devices in an integrated level. To achieve this goal, in what follows, different steps (including efficient guiding of light through the planar platform, efficient demultiplexing, and methods to flawlessly putting devices together) to realize this integrated platform will be discussed. Our research in this field has already resulted in a large number of scientific publications and technical presentations (18 journal papers and 41 conference presentations and invited talks). A complete list of journal papers and conference presentations is included at the end of this report. AFOSR support has been acknowledged in all these publications and presentations. Compared to other projects in Dr. Adibi's group and considering the level of funding, this project has been the most successful one. Two major patents (both pending) have been filed based on the results of this research.

The structure of this report is as follows. Since the details of the achievements in years 1 and 2 have already been reported in previous progress reports, they are not repeated here. Instead, a short itemized list of major achievements during this period is presented. The bulk of the report is then dedicated to the achievement in the period of October 2005 to April 2006 for which no previous report was submitted. Only major achievements with brief descriptions are listed in this report. Detailed information can be found in the recent publications or can be directly requested from Dr. Adibi.

II. Major Achievement During the 3-year AFOSR-Funded Research

This AFOSR-supported research was aimed at realizing several chip-scale optical devices needed as building blocks for implementing integrated optical systems. To achieve this, we developed several theoretical, fabrication, and characterization tools and procedures for photonic crystals. Some of the main achievements of the previous AFOSR-funded research at the device level are as follows:

- (1) *Photonic crystal waveguides (PCWs)* with low loss, large transmission bandwidth, and very low dispersion and distortion in their pass-band for efficient guiding of light; the bi-periodic PCW proposed and demonstrated in our research has shown the best performance among all proposed PCW structures in terms of low propagation loss and available guiding bandwidth;
- (2) *Photonic crystal superprism-based demultiplexers* for compact separation of spectral channels in an integrated platform; the focusing superprism idea proposed and experimentally demonstrated for the first time within this program carries the world record on PC demultiplexing in integrated platforms with at least two orders of magnitude smaller size (while having the same performance) compared to all existing implementations of the same structure;
- (3) Theoretical prediction of very compact *photonic crystal couplers* with performance that cannot be achieved in other integrated platforms;
- (4) Theoretical investigation and demonstration of *optical cavities with high quality factors*.

The fabrication techniques to reliably make these structures have also been optimized. The fabrication quality of the photonic crystal structures fabricated in our group recently is at the best level achieved in academia with similar fabrication equipment. The high fabrication quality of the structures is in part due to the available state-of-the-art JEOL electron beam lithography system at the microelectronic research center (MiRC) at Georgia Tech, the state-of-the-art inductively coupled plasma (ICP) etching machine owned by Adibi's group (acquired through an AFOSR DURIP grant), and our extensive efforts in the optimization of the fabrication process for the high-quality photonic crystal structures.

In addition, in this research the necessary simulation tools for the analysis and design of these photonic crystal components have been developed, and the characterization tools and techniques required for experimental validation have been matured.

III. Research Accomplishments

III.A Design of wideband single-mode photonic crystal waveguides (PCWs)

In the first two years of this program, we proposed that the dispersion of a photonic crystal waveguide (PCW) can be engineered by appropriate modification of the size or periodicity of the air holes close to the guiding region. The former perturbation resulted in single mode guiding and the latter in elimination of the modegap, dispersion linearization, and loss reduction. Knowing the individual roles of the hole size (r') and periodicity of holes (a') in the rows next to the guiding region on the properties of PCWs, it is essential to allow both parameters (or degrees of freedom) to vary simultaneously for a more careful optimization of PCWs. This task was done during the last year of the program. Figure 1 shows a scanning electron microscopy (SEM) image of these structures with definitions of the radii and the period of the air holes close to the guiding region.

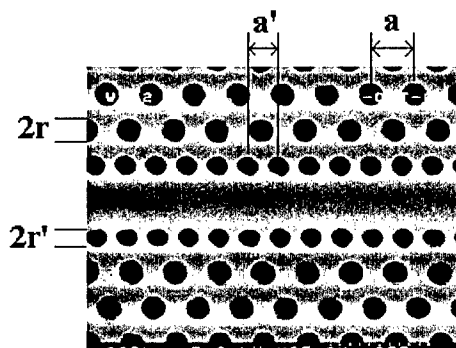


Figure 1. SEM view of a biperiodic photonic crystal waveguide is shown. The radius and the period of the air holes in the two rows next to the guiding region are $a'=0.7a$ and $r'=0.25a$, respectively, and the lattice constant is $a=420\text{nm}$.

Our approach is to allow both parameters to vary and find the single-mode guiding bandwidth below the light line for each set of (r', a') . Once we find PCWs with large bandwidths, we can also investigate the linearity of their dispersion and their coupling efficiency to an input slab waveguide to find the optimal PCW. The final results of this exhaustive search have been shown in Figures 2 and 3. The results in Figure 3 show that the single-mode guiding bandwidth of the biperiodic PCW has been extended to the entire frequency interval within the PBG and below the light line (maximum

achievable bandwidth); in addition, the dispersion is almost linear over the entire guiding bandwidth ($0.253 < a/\lambda < 0.268$) in this biperiodic PCW.

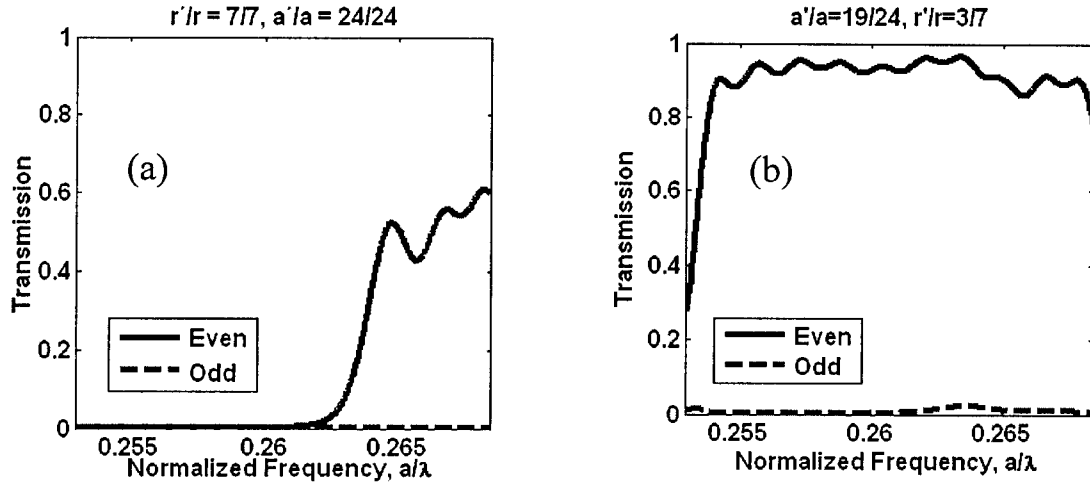


Figure 2. The normalized transmissions from a slab waveguide to a biperiodic PCW of the even and odd modes in the frequency range above the lower edge of the photonic bandgap (PBG) and below the light line for a) the conventional PCW ($r'/r, a'/a = (1,1)$) and b) a biperiodic PCW with $(r'/r, a'/a) = (3/7, 19/24)$; here r and a are the hole radius and lattice constant of the original photonic crystal. The biperiodic PCW has a larger single-mode guiding bandwidth with much better coupling to the input slab waveguide.

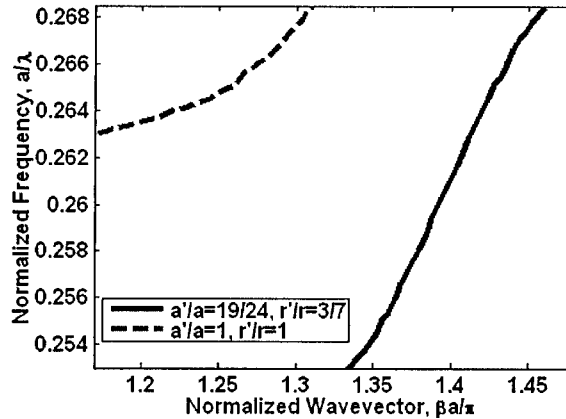


Figure 3. The dispersion diagrams of the even TM modes of the original PCW ($r'/r = a'/a = 1$) and a biperiodic PCW ($r'/r = 3/7$, $a'/a = 19/24$), where a is the lattice constant of the PCW.

III.B Design of high transmission and low dispersive PCW bend with large bandwidths

Waveguide bends are an important element in any integrated optics platform. There are various approaches in designing PCW bends. 1) They can be viewed as cavities coupling electromagnetic energy from the input to the output PCW. The transmission and dispersive properties of the bends are primarily determined by the modes and the quality factor (Q) of the cavity at the bend. The main disadvantage of the cavity based design of bends is the small bandwidth and high dispersion that are usually associated with high Q optical cavities. 2) Bends can also be designed based on the idea of impedance matching. The main idea is to use coupling holes to match the impedance of the bend region to those of the input and output waveguides. The idea is based on constructive

interference of multiple reflections in the matching region and hence suffers from the disadvantage of small bandwidth and large dispersion of the designed band. 3) Consider PCW bends as mirrors to deflect EM energy in the desired direction. Even though this idea seems simple to comprehend and works well for W3 and W5 waveguides, its drawback is low transmission for single mode W1 waveguides especially in the low group velocity region. Our idea is to use both group velocity and mode matching at the interface of the waveguide and the bend. By modifying the dispersion and mode properties of the guiding region and trying to match them to those of the incident region we can have high transmission through the bend with much lower dispersion for much larger bandwidth. Figure 4 shows our final bend design. Figure 5 shows the simulation results for our bend design compared to a simple bend in the single-mode guiding region of the PCWs attached to the bend region. Figure 5 clearly shows that our bend achieves a considerably larger high-transmission bandwidth and more importantly a linear dispersion (i.e., linear variation of phase with frequency) compared to the conventional bends, which is highly desired for practical applications.

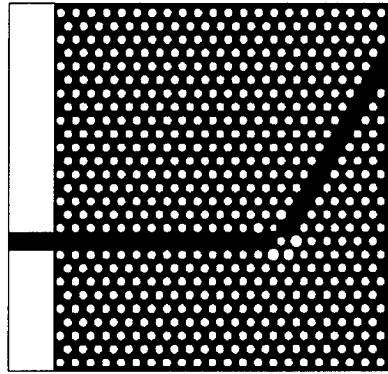


Figure 4. Layout of our bend design showing the modified holes at the bend region to achieve field matching between the two waveguides for wideband low-loss transmission.

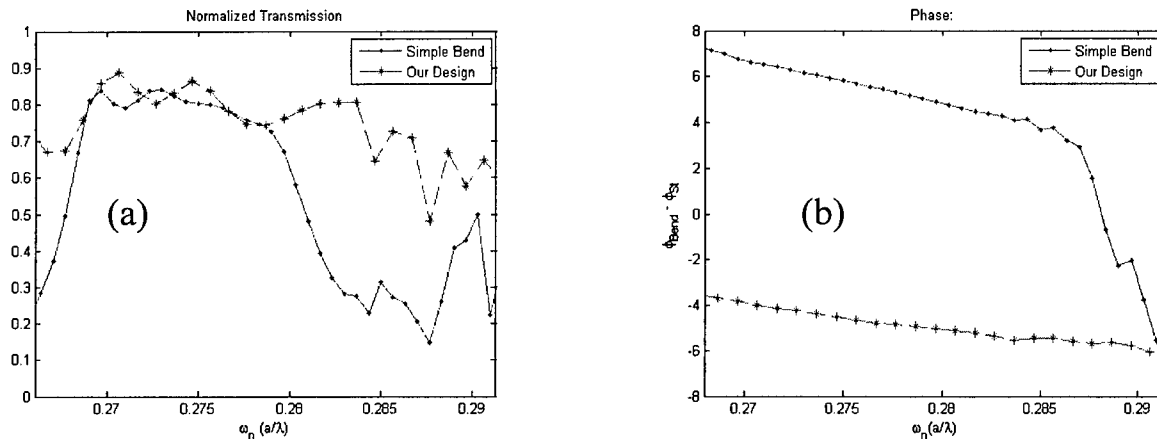


Figure 5. Comparisons of a simple waveguide bend (solid, marked by dots) and our designed bend based on field matching (dashed, marked by stars) are shown for (a) transmission spectrum and (b) phase response. Transmission bandwidth is improved using our design, and phase response is linear over the pass-band.

III.C Novel photonic structures based on critical coupling into cavities

Critical coupling is a particularly interesting phenomenon arising in systems of coupled waveguides and cavities. When a waveguide is coupled to a resonator, for example the side-coupling arrangement shown in Figure 6, a point can be reached where all of the power from the waveguide is coupled to the resonator. This “critical coupling” occurs when the coupling coefficient between the waveguide and the resonator is equal to the intrinsic loss of the resonator. If we choose the material of the resonator to have second-order nonlinear properties and assume that this “loss” is due to the conversion of optical power to the second harmonic frequency, this critically coupled system would be capable of significantly enhancing the conversion efficient for the second-harmonic generation (SHG) process. Such a system is easily and efficiently created using a suitable photonic crystal (PC) structure; however, the analysis is more straightforward when simple slab waveguides are used instead.

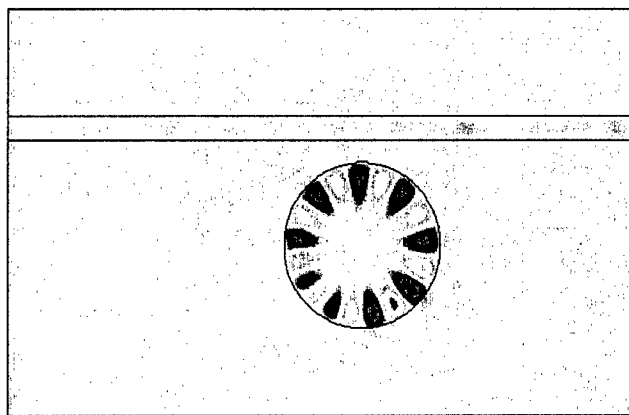


Figure 6. The field pattern of a conventional slab waveguide side-coupled to a microdisk resonator.

For the initial analysis of this application of critical coupling for efficient SHG, we have chosen to analyze a simple slab waveguide coupled to a “racetrack” or ring resonator, as shown in Figure 7. The modes of the linear resonator were calculated using our FDTD simulation tool, as shown in Figure 7(b). For the SHG simulations, $\chi^{(2)}$ nonlinear material was placed in the resonator in the region circled in red in Figure 7(a), as far as possible from the coupling region. This placement effectively decouples the coupling and loss mechanisms at the incident frequency (which includes the conversion to second harmonic), thus making the analysis of the system simpler. The transmission of the system calculated using the nonlinear FDTD is shown in Figure 7(c), where the SHG can clearly be seen at the higher frequencies. The ripples in the transmission curve represent noise in the simulation due to Fabry-Perot effects. Despite the strong SHG signal, the critical coupling point had not been reached, as evidenced by a coupling efficiency of less than 100% from the waveguide to the ring resonator at the resonant frequency.

We have analytically calculated the coupling coefficient and loss factor of the system in order to determine the appropriate nonlinear strength that should be used in the simulations, and are currently simulating structures using these values. Coupled mode theory was used to derive an expression for the coupling between the waveguide and the ring resonator for a given separation distance between the two waveguides. The loss due to SHG was calculated using the SHG conversion efficiency based on the mode mismatch between the fundamental and second-harmonic beams and by applying the condition that the “effective” loss should be equal to the calculated

coupling efficiency. The critical coupling structure will be next implemented using a PC waveguide coupling to a suitable PC cavity, and optimized for SHG efficiency using the nonlinear FDTD tool. It is expected that the overall device size will be considerably decreased by using PCs, due to the increased confinement of the optical power and the possibility of engineering the dispersion properties of the waveguides.

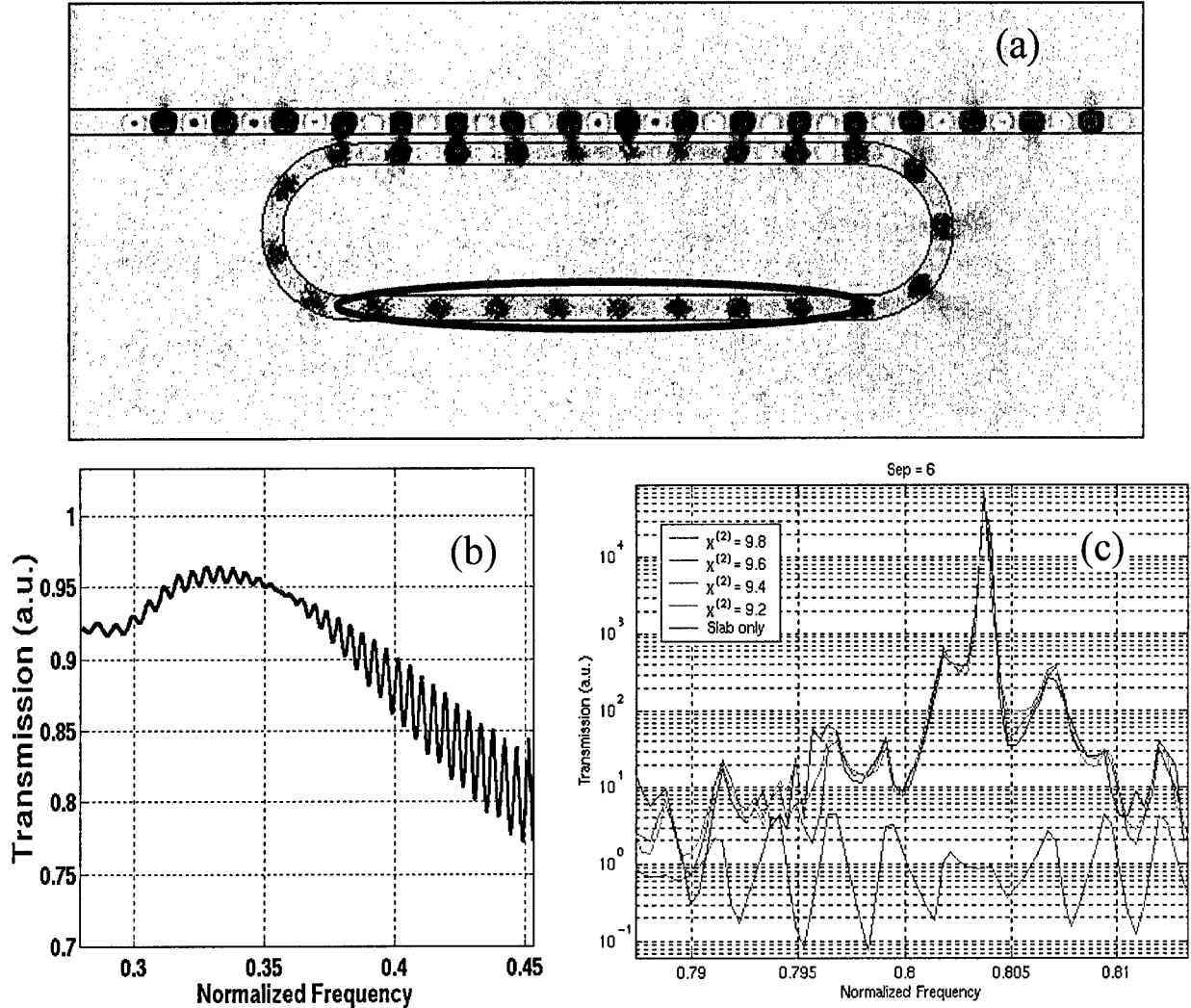


Figure 7. (a) The field pattern a conventional slab waveguide side-coupled to a ring resonator. (b) The calculated transmission of the coupled system, showing the dips in power at the resonance frequencies of the cavity. (c) The transmission of the $\chi^{(2)}$ nonlinear system, demonstrating the SHG effects.

III.D Wavelength demultiplexers based on preconditioned superprism effect in photonic crystals

Wavelength demultiplexing (WD) is one of the major applications of unique dispersion properties of the PCs. Possibility of integration and compactness are two main advantages of PC based demultiplexers compared to other demultiplexing techniques for applications including compact spectrometers (for sensing applications) and WDM demultiplexers. Proof-of-concept demonstrations of this phenomenon have been performed in planar structures. It has been shown

that the resolution requirement for these demultiplexers can result in a very large structure (on the order of cm^2 area), and phenomenological analysis shows that for a given operation bandwidth, the required area for this type of demultiplexers increases as the fourth power of the number of wavelength channels. These practical issues limit widespread use of these devices in current applications. We have shown that these limitations are caused by the choice of configuration and are not inherent to the photonic crystals. We have also proposed an alternative implementation that provides considerably improved performance compared to the conventional implementation in terms of being more compact and relaxed requirement for divergence angle of the incident beam.

In order to realize an efficient spectrometer, in addition to a compact WD mechanism to achieve spatial separation of different wavelength channels, special measures must be taken to achieve high isolation from unwanted wavelength channels. The basic demultiplexing function can be obtained using the superprism effect in PCs. Figure 8(a) shows a schematic demonstration of the superprism effect for wavelength demultiplexing, which is based on the difference between the dispersive properties of the PC and the incident region. Due to the superprism effect, different wavelength channels inside the PC region propagate in different directions (determined by the direction of group velocity of the corresponding PC mode at each wavelength). Propagation in such a medium can eventually result in separation of different wavelength channels, but it has been shown that the diffraction of the optical beam at each wavelength channel results in broadening of the beam, which requires relatively large propagation length to achieve spatial separation with the required cross-talk level between adjacent wavelength channels. More detailed analysis has shown limited resolution for compact PC WD devices based on the conventional configuration shown in Figure 8(a). In addition, it has been shown that the area of these demultiplexers increases as the fourth power of the number of channels (or equivalently, resolution), which limits their applicability for high-resolution purposes. Recently, it has been theoretically proposed that compact demultiplexers at high resolutions can be realized by combining two dispersive properties of PCs, i.e., superprism effect and negative diffraction. In these structures, the broadening of the beam due to normal diffraction effects is compensated by propagation in a PC region with negative diffraction, as shown in Figure 8(b). As a result of such diffraction compensation, the size of the beam at the output of these structures is reduced to approximately the transfer-limited beamwidth. This requires much smaller propagation length for spatial separation of adjacent wavelength channels. Another unique property of PCs is the negative refraction at their interface, as shown in Figure 8(c). In this case, the desired signal is refracted away from the direction of the incident signal, resulting in the separation of the desired signal from the stray signals.

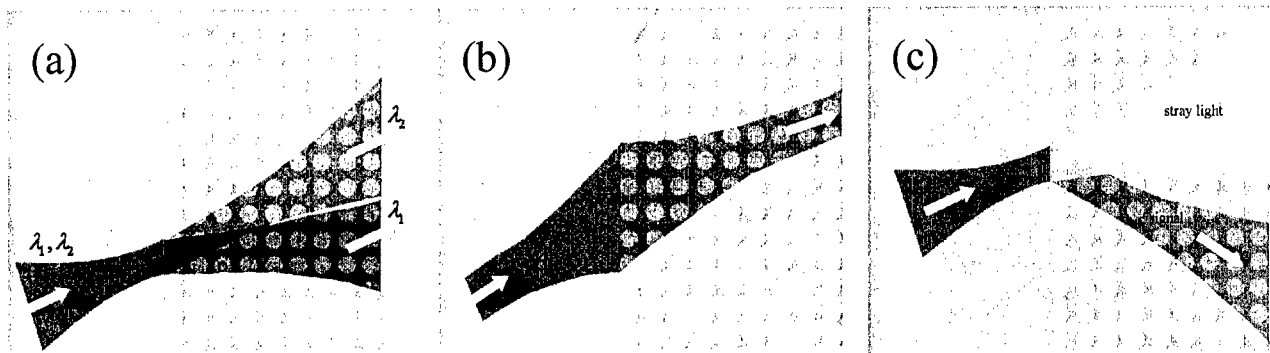


Figure 8. Three dispersive properties of PCs are schematically visualized: (a) the superprism effect, (b) the negative diffraction effect, and (c) the negative refraction effect.

We have recently shown (*Optics Express*, 14, 2413, 2006) that it is possible to combine several unique dispersive properties of PCs for a desired application by optimizing the PC geometry (i.e., size and periodicity of the holes). In particular, we show that it is possible to engineer the modes of the PC to simultaneously have the three aforementioned dispersive properties (i.e., superprism effect, negative diffraction, and negative refraction) at the frequency range of interest. By combining these three properties, it is possible to realize compact and efficient PC demultiplexers. By such optimal dispersion engineering in PC devices, it is possible to simultaneously focus the separated channels down to a small size while propagating through the PC and divert the separated channels from the stray and unwanted signals. These considerable improvements are obtained without adding to the complexity of fabrication or requiring any special material growth. This is a main advantage of PCs in which a wide range of material properties can be achieved by simply modifying the geometry of air holes.

Structures designed through optimization have been fabricated in SOI wafers (220nm Si, 3 μ m SiO₂ from SOITEC) using e-beam lithography and ICP etching facilities available through Microelectronic Research Center (MiRC) at Georgia Institute of Technology. Figure 9(a) shows the schematic view of the designed structure with incident light on the PC region coming from an unpatterned Si region and the output light going through an array of 5 μ m wide output waveguides (1 μ m distance between neighboring waveguides). Each output waveguide is tapered down to 2 μ m at the output end of the devices. The waveguide array has been designed to observe the output of the PC structure with a reasonable resolution. Each separated wavelength channel corresponds to two output waveguides to observe the possible crosstalk between adjacent channels more clearly. Two of the wavelength channels are schematically shown in Figure 9(a) as red and blue curves. Figure 9(b) shows the scanning electron microscopy (SEM) image of a portion of the PC structure (which has a 45° rotated square lattice geometry with a lattice constant of 367nm and with holes of 180nm in diameter) at its input interface. The SEM image of a portion of the output waveguide array is shown in Figure 9(c).

In our measurement setup, light from a tunable laser is end-coupled into the input Si region through a conventional dielectric ridge waveguide. The output edge of the device (which includes the waveguide array shown in Figure 9(a)) is imaged onto an infrared camera to record the results. The output from each waveguide is also isolated and measured using an infrared detector connected to a lock-in amplifier. Figure 10(a) shows the image of the output waveguides at four discrete wavelengths with input light having TE-like polarization (electric field parallel to the PC plane of periodicity in Figure 9(a)). Spatial separation of these wavelength channels can be clearly seen in Figure 10(a). In addition, the desired small spot from diffraction compensation is evident from this figure. Another evidence for dramatic minimization of the output spot size comes from the comparison of the focusing TE-like beams with TM-like (magnetic field parallel to the plane of periodicity) beams for which neither the superprism effect nor the diffraction compensation occur. In Figure 10(b), we show the measured output distributions for TM-like polarization for the same set of wavelengths used in Figure 10(a). It can be easily seen that the overall output beam profiles of all TM-like channels are very broad, covering more than 10 output waveguides. Comparing Figures 10(a) and 10(b), the effect of negative diffraction in refocusing the TE-like polarization beams at the output end is evident. Also, it can be clearly observed that by designing the device in the negative refraction regime for TE-like polarization, the unwanted polarization (TM) is

successfully isolated from the desired signals (i.e. all TM-like signals in the wavelength range of operation appear in a separate set of output waveguides numbered 12-24 as shown in Figure 10(b)).

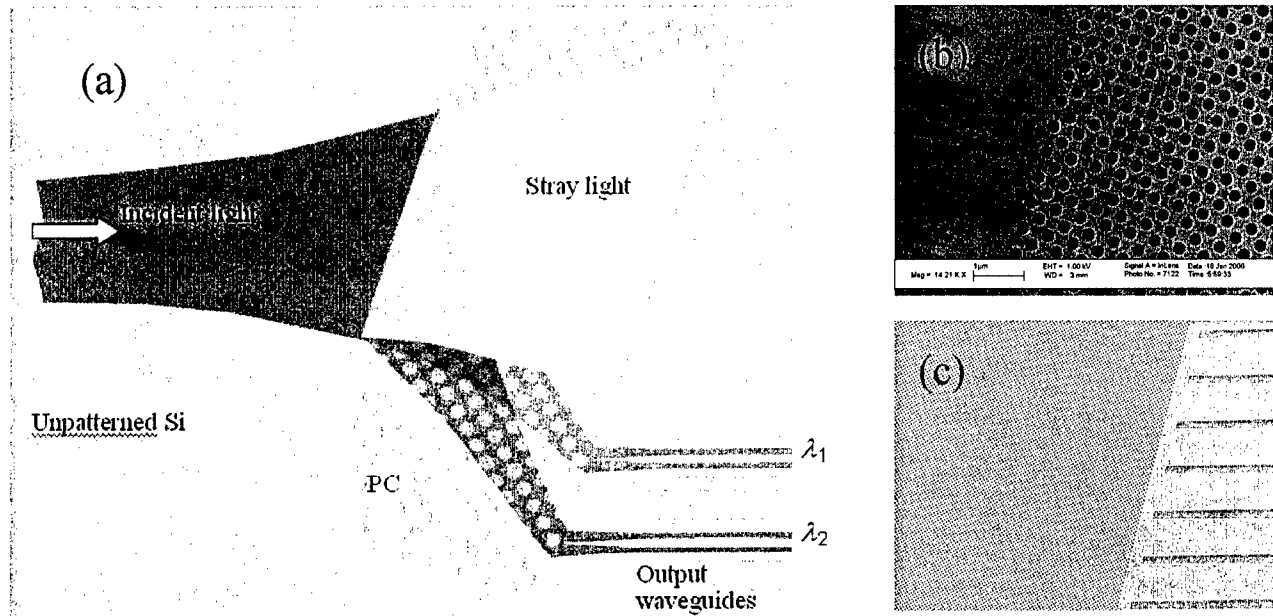


Figure 9. (a) The schematic layout of the PC demultiplexing device under consideration is demonstrated which shows the superprism effect, the negative diffraction effect, and the negative refraction effect simultaneously. (b) SEM image of the PC fabricated in an SOI substrate is shown. (c) SEM image of the output waveguide array in part (a) is shown.

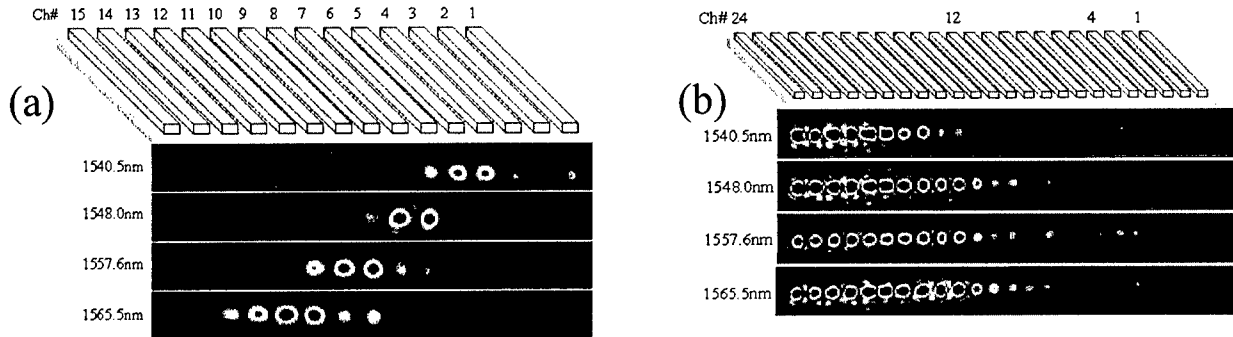


Figure 10. Images of the output face of the device (output power distribution from the array of waveguides) at four discrete wavelengths are shown for input beams with (a) TE-like polarization and (b) TM-like polarization at four different wavelengths.

To characterize our designed PC demultiplexer more quantitatively, we measured the power from each output waveguide by placing a pinhole in the far-field of the device output to select only a single waveguide and to reduce the scattered light from the background. The normalized measured power for four of the output waveguides are shown in Figure 11. Four channels are separated in this device with a wavelength spacing of 8nm, and channel isolations (i.e., the power in the desired channel divided by the sum of contributions of other channels at the location of the desired one) are better than 6.5dB. This integrated superprism-based demultiplexing device with 8 nm channel

wavelength separation takes PC area of less than $50\mu\text{m}\times 100\mu\text{m}$ (or $5000\text{ }(\mu\text{m})^2$). This is two orders of magnitude smaller than other experimental demonstrations of the superprism-based PC demultiplexers (in the conventional geometry) for the same performance. Using the same scheme, a 64-channel demultiplexer with channel spacing of 0.5 nm can be realized in a 4 mm^2 PC structure. To the best of our knowledge, this is the best overall performance for a PC demultiplexer reported to date.

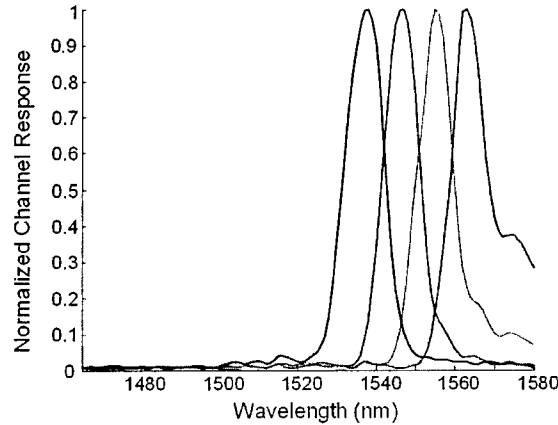


Figure 11. (a) Measured channel response of the four waveguides after normalization to the maximum transmission of each waveguide.

III.E Design of efficient photonic crystal couplers

We developed a systematic method for designing efficient directional couplers in photonic crystals. There are three issues need to be considered for designing a coupler. These issues are: 1) coupling length and the way to control it; 2) spectral characteristic of the coupler, in other words channel dropping bandwidth and channel spacing; and 3) design of the output circuit to send the desired signal outside of the coupling structure. To be close to a realistic device, the design of couplers in a triangular lattice photonic crystal of air holes in dielectric material is considered. The dielectric material throughout this paper is silicon with relative permittivity of $\epsilon=12.25$, and the material inside the holes is air with $\epsilon=1$. The radius of all air holes in the triangular-lattice photonic crystal used in this letter is $r=0.3a$ with a being the lattice constant of the structure.

Figure 12(a) shows the structure of a directional coupler where the size of the air holes in the intermediate region in the coupler has been changed. Figure 12(b) shows the dispersion of coupler for different sizes of the modified air holes. As it can be seen from Figure 12(b), by increasing the sizes of the intermediate air holes, two things happens. First, the frequency operation range of the coupler is shifted to higher values. Second, the coupling length becomes smaller, as demonstrated in Figure 12(c), which dramatically decreases the size of the coupler and makes the structure more compact.

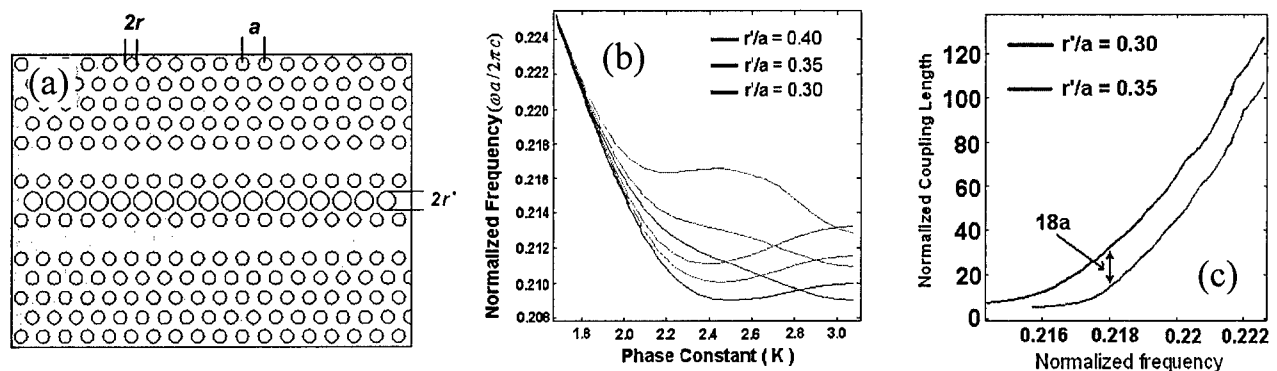


Figure 12. (a) Schematic illustration of a PC coupler in which the sizes of the intermediate air holes have been increased. (b) Dispersion of the modified coupler for different sizes of intermediate holes. (c) The coupling length of an unperturbed coupler is compared with that of a coupler with radius of the holes in the middle row changed to $r'=0.35a$.

A challenge in the design of directional couplers in photonic crystals is the design of a waveguide bend to guide the desired signal, which is coupled from one branch of the coupler to the other one, out of the coupling region. Figure 13(a) shows a typical design of a PC directional coupler together with the waveguide bend part. The structure consists of a triangular lattice photonic crystal of air holes in silicon. The radius of air holes (r) is 30% of the lattice spacing (a). Generally, in such a structure, the frequency operation range of the waveguide bend is different from the coupler operation frequency range as shown in Figure 13(b). As it can be seen from Figure 13(a), although a strong transmission occurs from one channel of the coupler to the other channel, the final transmission from the coupler to the waveguide bend is poor as the frequency range of high transmission for the coupler and the bend do not overlap. An optimal solution to improve the transmission of the signal from the coupler through the waveguide bend is to design the coupler and bend in a way to shift their operation frequency range toward each other so that a common frequency operation range for both structures is achieved. According to Figure 13(b), we need to shift down the operation frequency range of the bend and to shift up the operation frequency range of the coupler. Based on our theoretical studies and simulations we have succeeded to realize this appropriate frequency shift.

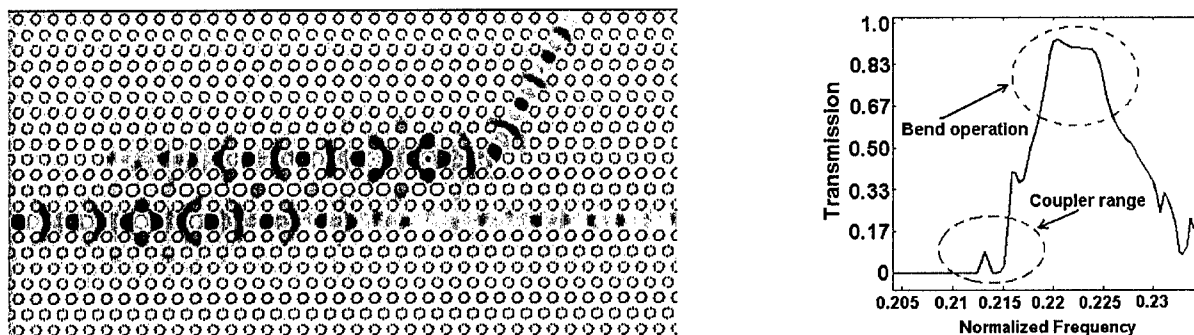


Figure 13. (a) Structure of a directional coupler together with bend waveguide. (b) Spectrum of the transmission of the bend; the frequency operation range of the coupler is also shown in this figure.

Figure 14(a) shows the structure of a waveguide bend after the modification in order to shift down the high transmission frequency range. These modifications are based on the properties of the original bend and the cavity that created in the bend corner. Therefore, knowing the properties of this cavity, by changing the sizes of the appropriate air holes in the bend region, the transmission frequency of bend is efficiently shifted down. Figure 14(b) shows the transmission of the bend structure before and after the modifications. Here, by combining the modified coupler and modified bend waveguide the efficient coupling structure is realized.

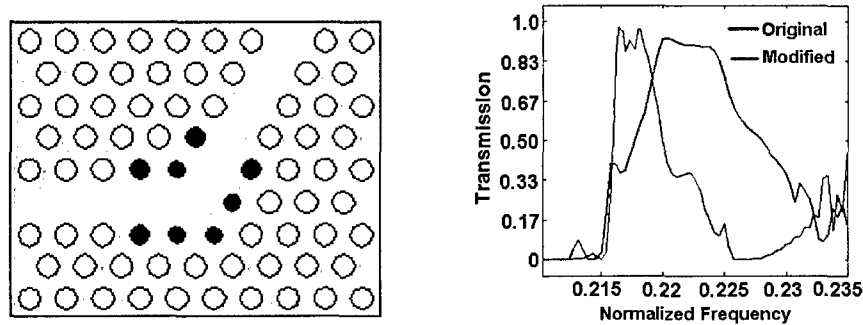


Figure 14. (a) Structure of the modified waveguide bend is shown. The air holes shown by green color have normalized radius of $r/a=0.22$, and the air holes shown by red color have normalized radius of $r/a=0.26$. (b) Spectrum of the transmission of the original bend and the modified bend. The high transmission frequency range of the modified bend overlaps considerably with that of the coupler.

IV. Publications and Presentations

While several projects are still ongoing and multiple publications in the near future are expected, the research supported by the AFOSR in the last year has resulted in 8 journal papers (4 published, 4 submitted), 9 conference presentations, and two invited talks. The following list includes all publications during the 3 year period of the program.

IV.A. Journal papers

1. N. Wu, M. Soltani, B. Momeni, M. Javanmard, A. Adibi, Y. Xu, and R. K. Lee, "General methods for designing single-mode planar photonic crystal waveguides in hexagonal lattice structures," *Optics Express*, vol. 11, pp. 1371-1377, 2003.
2. B. Momeni and A. Adibi, "Optimization of photonic crystal demultiplexers based on superprism effect," *Applied Physics B*, vol. 77, pp. 555-560, 2003.
3. A. Jafarpour, A. Adibi, Y. Xu, and R. K. Lee, "Mode dispersion in biperiodic photonic crystal waveguides," *Physical Review B*, vol. 68, pp. 233102-233105, 2003.
4. M. Soltani, A. Adibi, Y. Xu, and R. K. Lee, "Design of single-mode coupled resonator optical waveguides," *Optics Letters*, vol. 25, pp. 1978-1980, 2003.
5. A. Jafarpour, E. K. Chow, C. M. Reinke, J. Huang, A. Adibi, A. Grot, L. W. Mirkarimi, G. Girolami, Y. Xu, and R. K. Lee, "Large-bandwidth ultra-low-loss guiding in bi-periodic photonic crystal waveguides," *Applied Physics B*, vol. 79, pp. 409-414, 2004.

6. M. Badieirostami, B. Momeni, M. Soltani, A. Adibi, Y. Xu, and R. K. Lee, "Investigation of physical mechanisms in coupling photonic crystal waveguiding structures," *Optics Express*, vol. 12, pp. 4781-4789, 2004.
7. A. Jafarpour, C. M. Reinke, A. Adibi, Y. Xu, and R. K. Lee, "A new method for the calculation of the dispersion of nonperiodic photonic crystal waveguides," *IEEE Journal of Quantum Electronics*, vol. 40, pp. 1060-1067, 2004.
8. A. Jafarpour, E. Chow, C. M. Reinke, J. D. Huang, A. Adibi, A. Grot, L. W. Mirkarimi, G. Girolami, R. K. Lee, and Y. Xu, "Large-bandwidth ultra-low-loss guiding in bi-periodic photonic crystal waveguides," *Applied Physics B*, vol. 79, pp. 409-414, 2004.
9. B. Momeni and A. Adibi, "An approximate effective index model for efficient analysis and control of beam propagation effects in photonic crystals," *Journal of Lightwave Technology*, vol. 23, pp. 1522-1532, 2005.
10. B. Momeni and A. Adibi, "Systematic design of superprism-based photonic crystal demultiplexers," *IEEE Journal of Selected Areas in Communications*, vol. 23, pp. 1355-1364, 2005.
11. B. Momeni and A. Adibi, "Adiabatic matching stage for coupling of light to extended Bloch modes of photonic crystals," *Applied Physics Letters*, vol. 87, pp. 171104-171106, 2005.
12. C. M. Reinke, A. Jafarpour, B. Momeni, M. Soltani, S. Khorasani, A. Adibi, Y. Xu, and R. K. Lee, "Nonlinear finite-difference time-domain simulation of $\chi^{(2)}$ and $\chi^{(3)}$ effects in two-dimensional photonic crystals," *IEEE Journal of Lightwave Technology*, vol. 24, no. 1, pp. 624-634, 2006.
13. J. Huang, C. M. Reinke, A. Jafarpour, B. Momeni, M. Soltani and A. Adibi, "Observation of large parity-change-induced dispersion in triangular-lattice photonic crystal waveguides using phase sensitive techniques," *Applied Physics Letters*, vol. 88, pp. 071111-1-3, 2006.
14. B. Momeni, J. Huang, M. Soltani, M. Askari, S. Mohammadi, M. Rakhshandehroo, and A. Adibi, "Compact wavelength demultiplexing using focusing negative index photonic crystal superprisms," *Optics Express*, vol. 14, no. 6, pp. 2413-2422, 2006.
15. B. Momeni and A. Adibi, "Demultiplexers harness photonic-crystal dispersion properties," *Laser Focus World* **42**, 125-128 (2006).
16. B. Momeni and A. Adibi, "Preconditioned superprism-based photonic crystal demultiplexers: Analysis and design," accepted for publication in *Applied Optics*, 2006.
17. A. Jafarpour, A. Adibi, and Y. Xu, "Optimization of Photonic Crystal Waveguides with Two Degrees of Freedom," submitted to *Optics Communications*, 2006.
18. B. Momeni, A. A. Eftekhari, and A. Adibi, "Effective impedance model for analysis of reflection at the interfaces of photonic crystals," submitted to *Optics Letters*, 2006.

IV.B. Conference presentations

1. A. Jafarpour, M. Soltani, B. Momeni, A. Adibi, Y. Xu, and R. Lee, "Controlling mode properties in photonic crystal waveguides," *PECS-IV: International Workshop on Photonic and Electromagnetic Crystal Structures*, Los Angeles, CA, October 2002.

2. B. Momeni, M. Soltani, and A. Adibi, "Efficient computation of band structure in photonic crystals," *Optics in the Southeast*, Huntsville, AL, October 2002.
3. B. Momeni and A. Adibi, "Engineering the bandgap in photonic crystals," *OSA Annual Meeting*, Orlando, FL, October 2002.
4. M. Soltani, A. Haque, B. Momeni, A. Adibi, Y. Xu, and R. Lee, "Single mode design of photonic crystal waveguides," *OSA Annual Meeting*, Orlando, FL, October 2002.
5. M. Soltani, A. Haque, B. Momeni, A. Adibi, Y. Xu, and R. K. Lee, "Designing complex optical filters using photonic crystal microcavities," *Proceedings of the SPIE*, vol. 5000, Photonic Crystal Materials and Devices, pp. 257-265, 2003.
6. C. M. Reinke, A. Jafarpour, B. Momeni, M. Soltani, S. Khorasani, A. Adibi, R. Lee and Y. Xu, "A finite difference time domain code for simulation of $\chi^{(2)}$ and $\chi^{(3)}$ nonlinear effects in two-dimensional non-homogeneous optical structures," *The Second IMACS International Conference on Nonlinear Evolution Equations and Wave Phenomena: Computation and Theory*, April 2003.
7. B. Momeni, C. M. Reid, A. Adibi, M. E. Sullivan, and D. J. Brady, "Unique Dispersion Properties of Photonic Crystals: Properties and Applications," *Fitzpatrick Annual Symposium*, Durham, NC, May 2003.
8. M. Soltani, B. Momeni, A. Adibi, Y. Xu, and R. K. Lee, "Single mode design and dispersion control of coupled resonator optical waveguides in photonic crystals," *CLEO/QELS*, Baltimore, MD, 2003.
9. B. Momeni and A. Adibi, "Optimization of superprism-based photonic crystal demultiplexers," *CLEO/QELS*, Baltimore, MD, 2003.
10. B. Momeni and A. Adibi, "Systematic design of superprism-based photonic crystal demultiplexers," *OSA Annual Meeting*, Tucson, AZ, October 2003.
11. C. M. Reinke, M. Soltani, B. Momeni, A. Jafarpour, S. Khorasani, A. Adibi, Y. Xu, and R. K. Lee, "Analysis of $\chi^{(3)}$ nonlinear effects in select two-dimensional photonic crystal structures," *OSA Annual Meeting*, Tucson, AZ, October 2003.
12. M. Badieirostami, B. Momeni, A. Adibi, Y. Xu, and R. K. Lee, "Fundamental physical coupling mechanisms in photonic crystal waveguides," *OSA Annual Meeting*, Tucson, AZ, October 2003.
13. B. Momeni and A. Adibi, "Controlling diffraction of optical beams using photonic crystals," *Proceedings of the SPIE*, vol. 5360, *Quantum Sensing and Nanophotonic Devices*, pp. 355-363, 2004.
14. B. Momeni and A. Adibi, "An effective index model for efficient analysis of light propagation in photonic crystals," *PECS-V: International Workshop on Photonic and Electromagnetic Crystal Structures*, Kyoto, Japan, March 2004.
15. C. M. Reinke, J. Huang, B. Momeni, M. Soltani, A. Jafarpour, and A. Adibi, "Low-loss and wideband guiding in photonic crystal structures for integrated optics applications" *4th Annual Fitzpatrick Center Meeting*, Duke University, Durham, NC, May 2004.

16. A. Jafarpour, C. M. Reinke, B. Momeni, M. Soltani, J. Hunag, and A. Adibi, "Integrated chip-scale WDM devices using photonic crystals," *4th Annual Fitzpatrick Center Meeting*, Duke University, Durham, NC, May 2004.
17. C. M. Reinke, A. A. Jafarpour, J. D. Huang, and A. Adibi, "Optical transmission and phase jitter measured in triangular-lattice photonic crystal waveguides," *OSA Annual Meeting*, Tucson, AZ, October 2004.
18. E. Shah Hosseini, and A. Adibi, "Switching Devices Utilizing Mode Engineering in Photonic Crystal Cavities," *Optics in the Southeast*, Charlotte, NC, November 2004.
19. A. A. Eftekhar, A. Adibi, "An efficient method for calculation of radiation pattern of sources inside planar photonic Crystal slabs," *Optics in the Southeast*, Charlotte, NC, November 2004.
20. A. A. Eftekhar, A. Adibi, "Efficient computation of Green's function for two dimensional photonic crystal slabs", *Photonics West*, San Jose, CA, January 2005.
21. B. Momeni and A. Adibi, "Adiabatic Coupling to Extended Bloch Modes of Photonic Crystals," *Photonics West*, San Jose, CA, January 2005.
22. A. Jafarpour, A. Adibi, Y. Xu, and R. K. Lee, "Integrated optical functionalities featuring bi-periodic photonic crystals," *Conference on Lasers and Electro Optics (CLEO)*, Baltimore, MD, May 2005.
23. B. Momeni, A. A. Eftekhar, and A. Adibi, "Design of adiabatic matching stages for efficient light coupling to propagating modes of photonic crystals," *Conference on Laser and Electro Optics (CLEO)*, Baltimore, MD, May 2005.
24. A. Jafarpour, C. M. Reinke, J. Huang, A. Adibi, Y. Xu, and R. K. Lee, "Optimization of Mode Dispersion, Propagation Loss, and Guiding Bandwidth in Photonic Crystal Waveguides," *International Symposium on Photonic and Electromagnetic Crystal Structures (PECS VI)*, Aghia Pelaghia, Greece, June 2005.
25. B. Momeni and A. Adibi, "Compact photonic crystal demultiplexers based on focusing superprism effect," *International Symposium on Photonic and Electromagnetic Crystal Structures (PECS VI)*, Aghia Pelaghia, Greece, June 2005.
26. B. Momeni, M. Soltani, M. Askari, D. K. Brown, and A. Adibi, "Ultracompact preconditioned superprism-based photonic crystal demultiplexers," *LEOS 2005 (18th IEEE LEOS Annual Meeting)*, Sydney, Australia, 2005.
27. A. Jafarpour, A. Adibi, Y. Xu and R. K. Lee, "Mode Engineering in Ultra-Low Loss Bi-periodic Photonic Crystal Waveguides," *18th IEEE LEOS Annual Meeting*, Sydney, Australia, 2005.
28. C. M. Reinke, J. D. Huang, A. A. Jafarpour, B. Momeni, M. Soltani and A. Adibi, "Observation of large group delay in triangular-lattice photonic crystal waveguides using phase sensitive lock-in techniques," *Optics in the Southeast*, Atlanta, GA, October 2005.
29. B. Momeni and A. Adibi, "Investigation of reflection at the interface of photonic crystals," *Optics in the Southeast*, Atlanta, GA, October 2005.

30. A. Jafarpour, A. Adibi, Y. Xu and R. K. Lee, "Theoretical and experimental study of mode dispersion in biperiodic photonic crystal structures," *Proceedings of SPIE*, vol. 6128, 2006.
31. B. Momeni, M. Badiei, J. Huang, M. Soltani, M. Askari, S. Mohammadi, E. Shah Hosseini, and A. Adibi, "Compact Spectrometers Based on Focusing Superprism Effect in Photonic Crystals for Integrated Sensing Applications," *Conference on Lasers and Electro Optics (CLEO)*, Long Beach, CA, 2006.
32. B. Momeni, J. Huang, M. Soltani, M. Askari, S. Mohammadi, and A. Adibi, "Compact Photonic Crystal Superprism Demultiplexers based on Diffraction Compensation," *Conference on Lasers and Electro Optics (CLEO)*, Long Beach, CA, 2006.
33. A. Jafarpour, J. Huang, M. Askari, and A. Adibi, "Real-time spectral phase measurement in nano-scale optical waveguides," *Proceedings of Seeing at the Nanoscale Conference* (held by Veeco Instruments), 2006.
34. B. Momeni, C. M. Reinke, M. Soltani, M. Askari, S. Mohammadi, E. Shah Hosseini, M. Badieirostami, J. Huang, and A. Adibi, "Compact Integrated Photonic Crystal Spectrometers for Sensing Applications," *6th Annual Southeast Multiphoton Confocal Microscopy Workshop*, Atlanta, GA, 2006.

IV.C. Invited talk

1. A. Adibi, B. Momeni, M. Soltani, A. Jafarpour, C. M. Reinke, Y. Xu, and R. K. Lee, "Design of electromagnetic modes in photonic crystal devices," *Micromachining Technology for Microoptics and Nanooptics Conference in Photonics West Meeting 2003*, San Jose, CA, January 2003.
2. A. Adibi, B. Momeni, M. Soltani, A. A. Jafarpour, C. M. Reinke, Y. Xu, and R. K. Lee, "Design and characteristics of photonic crystal devices" *Micromachining Technology for Microoptics and Nanooptics Conference in Photonics West Meeting 2004*, San Jose, CA, January 2004.
3. A. Jafarpour, C. M. Reinke, B. Momeni, M. Soltani, J. Hunag, and A. Adibi, "Integrated chip-scale WDM devices using photonic crystals," *4th Annual Fitzpatrick Center Meeting*, Duke University, Durham, NC, May 2004.
4. A. Jafarpour, C. M. Reinke, A. Adibi, Y. Xu, and R. K. Lee, "A spatial Fourier transform technique for the analysis of general photonic crystal waveguides" *SIAM conference on Mathematical Aspects of Materials Science*, Los Angeles, CA, May 2004.
5. A. Adibi, B. Momeni, A. Jafarpour, C. M. Reinke, and M. Soltani, "Novel optical devices based on dispersion engineering in photonic crystals," *Optics in the Southeast*, Charlotte, NC, November 2004.
6. C. M. Reinke, A. Jafarpour, J. Huang, M. Soltani, B. Momeni, A. Adibi, R. Norwood, and N. Peyghambarian, "Integrable planar photonic crystal devices in silicon using nonlinear effects," *LEOS 2005 (18th IEEE LEOS Annual Meeting)*, Sydney, Australia, 2005.
7. B. Momeni, J. Huang, M. Soltani, M. Askari, S. Mohammadi, A. Adibi, "Compact preconditioned photonic crystal demultiplexers based on combined focusing and superprism effects," *Photonics West Meeting*, San Jose, CA, January 2006.

/O=ORGANIZATION/OU=OH ADMIN GROUP/CN=RECIPIENTS/CN=TARRIE.SIMS

From: Gernot Pomrenke [gpomrenke@msn.com]
Sent: Tuesday, December 12, 2006 11:17 AM
To: Sims, Tarrie D Civ AFRL/AFOSR
Subject: Sick Leave

Tarrie,

I am taking a day of sick leave, today Tuesday, 12 Dec.

Regards,
Gernot

12/13/2006